A Downlink Switched-Beam OFDM Pilot Scheme Based on Subcarrier-Multiplexing

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Abstract— **In this paper, we explore the use of the OFDM symbol structure to both select the beam and estimate the channel on the downlink of an OFDM switched-beam system. The channel estimation and beam selection use special OFDM pilot symbols which consist in beam-specific pilot samples frequency multiplexed on the available downlink subcarriers. At the reception, beam channels seen on each subcarrier are estimated, then the best serving beam is selected. For equalization purposes, an interpolation is used between channel estimates for the selected beam, to obtain the missing beam channel estimates on the subcarriers that were allocated to other beams on the pilot symbol. In contrast to previous works, which assumed an uplink/downlink channel symmetry to select the serving beam from uplink measurements, our proposition considers the use of the MISO downlink channel measurements obtained at the mobile. It is the mobile that identifies the best-serving beam and requests that beam.**

I. INTRODUCTION

Smart antennas will be a key component in future high-capacity wireless cellular networks [1]. Smart-antennas may be used on the downlink to introduce spatial diversity, to allow spatial multiplexing, or, when the spatial correlation between the channels seen by the different antenna elements is high, to do beamforming [2]. One simple variant of the beamforming technique, called switched-beam beamforming [3], consists in transmitting using the most appropriate beam, selected periodically from a set of predefined beams. The main advantages of such a beamforming approach are the ease of implementation in existing networks, and the relatively small amount of additional signaling required [3, 4].

One important issue in switched-beam systems is the beam selection process. In [3], the authors propose to use the beam signal strength received in the uplink to select the appropriate downlink beam. In CDMA networks, dedicated channels, such as the S-CIPCH, are used for beam selection [5, 6]. Although OFDM has received a lot of attention recently due to its simplicity of implementation [7] and its resistance to ISI in severe multipath environments [8], very little work has been done in the context of beam selection for OFDM systems. Switched-beam beam selection for OFDM systems was addressed in [9]. That work suggested the use of two measurements, the received signal strength and the peak-to-trough ratio (PTR), extracted from the uplink frame preamble used in 802.11a and 802.16 systems. Once more, the beam selection process was mainly based on the uplink/downlink channel symmetry, which is not always an appropriate assumption [10]. To the best of our knowledge, the OFDM symbol structure was never considered or exploited in a beam selection process.

In this paper, we explore the use of the OFDM symbol structure to both select the beam and estimate the channel on the downlink of an OFDM switched-beam system. The channel estimation and beam selection use special OFDM pilot symbols which consist in beam-specific pilot samples frequency multiplexed on the available downlink subcarriers. At the reception, beam channels seen on each subcarrier are estimated, then the best serving beam is selected. For equalization purposes, an interpolation is used between channel estimates for the selected beam, to obtain the missing beam channel estimates on the subcarriers that were allocated to other beams on the pilot symbol. In contrast to previous works, which assumed an uplink/downlink channel symmetry to select the serving beam from uplink measurements, our proposition considers the use of the MISO downlink channel measurements obtained at the mobile. It is the mobile that identifies the best-serving beam and requests that beam. Note that the same pilot symbols are used both for the beam selection and the channel estimation.

The structure of the paper is as follows. The system is described in section 2, and the channel estimation and beam selection procedure is detailed in section 3. Simulation results are presented in section 4. Conclusions are outlined in section 5.

II. SYSTEM MODEL

We consider the downlink, where a mobile has a single isotropic antenna surrounded by uniformly distributed scatterers [11]. On the other hand, the base station, which is located high enough not to be shadowed by local scatterers (e.g. on a tower), transmits using multiple isotropic antennas. Furthermore, the base station and the mobile are supposed far enough from one another as to create a near planar wavefront over the antenna array surface.

We use an OFDM-based system with multiple antennas at the transmission and a single antenna at the reception, as presented in figure 1. We assume that there are A antennas at the transmission. Our switched-beam system uses B beams per sector. The system uses a periodically transmitted OFDM pilot symbol which is composed of subcarrier samples associated with specific beams, frequency multiplexed over the subcarriers. More specifically, the pilot symbol for beam b is defined as $\mathbf{p}_b = [p_{b,1}, \ldots, p_{b,i}, \ldots, p_{b,N}]^T$, where i denotes the subcarrier index; N is the number of subcarriers; $p_{b,i} = \delta_{\text{mod}(i-b,B),0}\, p$; $\delta_{(\cdot)}$ is the Kronecker delta function; and p is a scalar. Figure 2 shows the resulting pilot scheme. The total pilot symbol transmitted from antenna a is then

$$\mathbf{s}_a = \sum_{b=1}^{B} w_{a,b}\mathbf{p}_b, \qquad (1)$$

where $w_{a,b}$ is the component of the steering vector at antenna a associated with the b^{th} fixed-beam. The frequency separation between the pilot samples associated with a given beam provides frequency diversity in the beam selection and channel estimation processes.

If we now look at the data symbols, we note that, in a real cellular system, a given cell will accommodate multiple users, and,

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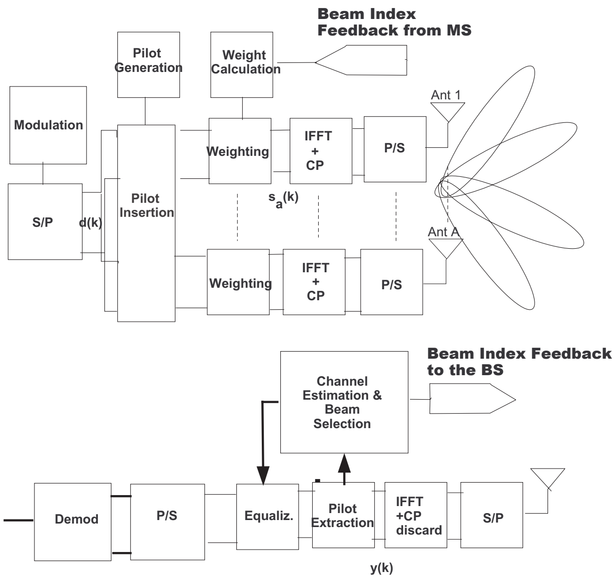

Fig. 1. OFDM MISO system with switched-beams.

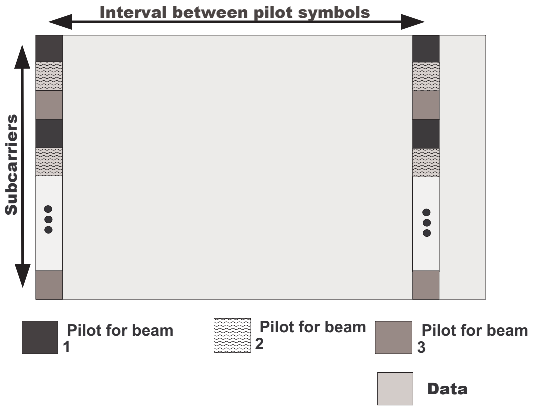

Fig. 2. Pilot scheme.

in fact, multiple users can also be assigned to the same fixed-beam. The signal sent on a specific beam then results from a combination of the symbols sent to all users associated with that beam, with the considered multi-access scheme. The multi-access scheme could be TDMA, CDMA, OFDMA, or even hybrid versions. To simplify the presentation, we will assume here that there is a single user, and we will omit to refer specifically to the type of multi-access used, by looking, in the simulation section, only to the single-user link performance without multi-access. System-level performance with multi-access, and related issues, will be studied in a future publication. Under our single-user assumption, a single fixed-beam is used at any given time during data transmission. If we denote the k^{th} OFDM data symbol to be transmitted by $\mathbf{d}(k) = [d_1(k), \ldots, d_i(k), \ldots, d_N(k)]^T$, we have the following transmitted signal on the a^{th} antenna branch:

$$\mathbf{s}_a(k) = w_{a,\tilde{b}(k)}\mathbf{d}(k), \qquad (2)$$

where $\tilde{b}(k)$ is the beam index of the active switch-beam, as a function of k.

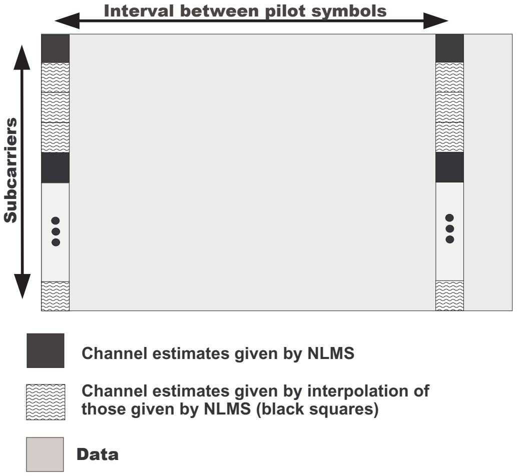

Fig. 3. Channel estimation procedure.

In the following, we use a notation similar to [12] generalized to MISO systems. After the FFT at the receiver of the user located in the β^{th} beam, the processed symbol $\mathbf{y}_\beta(k)$ can be written as:

$$\mathbf{y}_\beta(k) = \sum_{a=1}^{A} \mathbf{H}_{a,\beta}(k)\mathbf{s}_a(k) + \mathbf{F}_N\boldsymbol{\nu}_\beta(k), \qquad (3)$$

where $\mathbf{H}_{a,\beta}(k)$ is a diagonal matrix containing the transformed channel coefficients in the frequency domain between the a^{th} antenna and the user in the β^{th} beam. The vector $\boldsymbol{\nu}_\beta(k)$ is associated with the Gaussian white noise. The matrix $\mathbf{F}_N$ is the $N \times N$ Fourier matrix defined such that its m^{th} column is given by $[1, \omega^m, \omega^{2m}, \ldots, \omega^{(N-1)m}]^T$, where $\omega = e^{-\frac{j2\pi}{N}}$.

Using (1) and (2), (3) can be reformulated as:

$$\mathbf{y}_\beta(k) = \sum_{b=1}^{B}\sum_{a=1}^{A} w_{a,b}\mathbf{H}_{a,\beta}(k)\mathbf{p}_b + \mathbf{F}_N\boldsymbol{\nu}_\beta(k), \qquad (4)$$

when k corresponds to a pilot symbol, and as

$$\mathbf{y}_\beta(k) = \sum_{a=1}^{A} w_{a,\tilde{b}(k)}\mathbf{H}_{a,\beta}(k)\mathbf{d}(k) + \mathbf{F}_N\boldsymbol{\nu}_\beta(k), \qquad (5)$$

when k corresponds to data symbols.

Finally, by taking the diagonal matrix $\mathbf{H}_{b,\beta}(k) = \sum_{a=1}^{A} w_{a,b}\mathbf{H}_{a,\beta}(k)$, (4) and (5) are transformed into:

$$\mathbf{y}_\beta(k) = \sum_{b=1}^{B} \mathbf{H}_{b,\beta}(k)\mathbf{p}_b + \mathbf{F}_N\boldsymbol{\nu}_\beta(k), \qquad (6)$$

and

$$\mathbf{y}_\beta(k) = \mathbf{H}_{\tilde{b}(k),\beta}(k)\mathbf{d}(k) + \mathbf{F}_N\boldsymbol{\nu}_\beta(k), \qquad (7)$$

respectively.

III. BEAM SELECTION AND CHANNEL ESTIMATION

A complete periodically transmitted OFDM symbol is used as a pilot to estimate the channel and select the serving beam. At the reception, a NLMS algorithm [13] is used to estimate the beam channel of every fixed-beam at the associated subcarrier indices. Assuming the beam b, the algorithm is run throughout the following steps for each subcarrier i

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for $k = 1, 2, 3, ...$
    if mod$(i - b, B) = 0$
        $e_{b,i}(k+1) = y_i(k+1) - p\hat{h}_{b,i}(k)$
        $\hat{h}_{b,i}(k+1) = \hat{h}_{b,i}(k) + \mu \frac{e^*_{b,i}(k+1)}{p^*}$
    else
        $\hat{h}_{b,i}(k+1) = 0$
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where $e_{b,i}(k)$ is the estimation error at time k (pilot symbol index) at subcarrier i, μ is the adaptation step, and $\hat{h}_{b,i}$ is the estimation, in the frequency domain, of the b^{th} beam channel along its i^{th} subcarrier. Note that, to simplify the notation, we have omitted the index β. Once the estimates of all beam channels are available, we compute the average power associated with each beam. Then, the beam with maximal power, $\tilde{b}$, is chosen according to the following:

$$\tilde{b}(k) = \underset{b \in [1:B]}{\text{arg\_max}} \quad \frac{1}{N} \sum_{i=1}^{N} |\hat{h}_{b,i}(k)|^2. \qquad (8)$$

The beam index $\tilde{b}(k)$ is then fed back to the transmitter, which uses the corresponding beam for the following symbols.

After selecting the best serving beam, the mobile needs to estimate the channel in the subcarriers that were allocated to the other beams. For this purpose we use a spline interpolation between these subcarriers to obtain the channel estimates on all subcarriers. Note that we chose to use circularity to do the interpolation of the last (or the first) subcarriers, i.e., we interpolate them by duplicating the first (or the last) channel estimates, respectively. Figure 3 illustrates the channel estimation process, identifying the estimates obtained via NLMS for the first beam, and the channel estimates obtained via interpolation for that same beam. Note that the channel estimates are held constant during the data symbols, up to the next pilot symbol.

IV. SIMULATIONS

The following parameters are used in our Monte-Carlo simulations:

- A 64 point FFT transform with an OFDM symbol (16-QAM) of duration $T_s = 0.2\mu s$, and a cyclic prefix of length equal to 1/4 of the total OFDM symbol.
- A total of 10000×64×4 =2.560.000 transmitted bits.
- We consider the single-user case.
- The system is operating at 5GHz.
- The pilot rate is 10%.
- The channel model is described in [14] with an angular spread $\sigma_\theta = 1.06^o$[1]. It is made of 3 paths with an exponentially decaying power profile. The second path has a relative delay of $2T_s$ with a relative attenuation of $3dB$, relative to the first path, and the third has a delay of $6T_s$ with an attenuation of $6dB$, still relative to the first path. The total transmitted power for a given user is normalized to 1. To simplify the interpretation of the results we consider that the paths have the same Laplacian angular distribution with the same mean angle of arrival that sweeps the entire sector of $\frac{2\pi}{3}rad$ during the simulation time of $10000 \times (64+16) \times T_s$ (16 is the cyclic prefix length).
- 4 antennas are used. They are separated by half a wavelength and create a 4-beam pattern according to the Butler proposition [15].

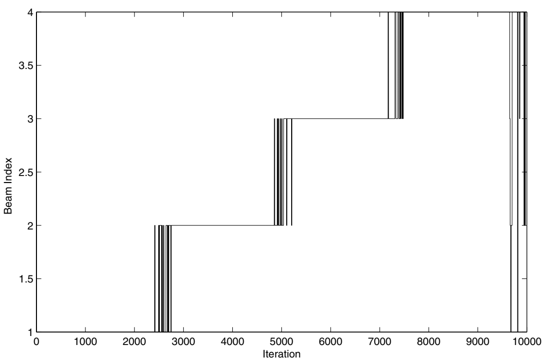

Fig. 4. Evolution of beam index for 3kmph in a noisy environment (SNR of 0dB).

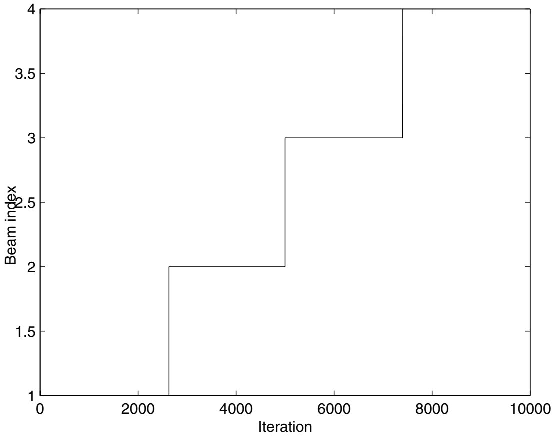

Fig. 5. Evolution of beam index for 3kmph in a "clean" environment (SNR of 30dB).

- We used $\mu = 1$ in NLMS.

We first look at the performance of our proposed scheme in terms of beam selection. Figures 4 and 5 plot the evolution of the beam index, for a mobile moving at a speed of 3kmph, in both a noisy (SNR of 0dB), and a "clean" (SNR of 30dB) environment, respectively. The effect of higher speeds can be seen in figures 6 and 7.

One can conclude that the method is more resistant to noise effects at lower speeds. The noise affects the choice of the beam especially in transition zones where two beams have almost the same average power. Our beam selection has the advantage of always tracking the best serving beam, in contrast to beam selection done according to the angular position of the mobile. In other words, when the used beam falls into a fade, then our system switches to the best beam for which the fade did not occur.

The overall performance of the system, in terms of BER versus SNR, for the two previously considered mobile speeds, is illustrated in figure 8. Note that zero forcing equalization is used. We compare the performance of our system with the performance that would be obtained if the channel was still estimated using NLMS, but the beam was to be selected depending on the angular position of the mobile (called Angular Position in the figure). Such a beam decision

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[1] The inner parameters of the channel model of [14] are set to $K = 10$, $\kappa = 0$, $\sigma_d = 2.65$ and $\Delta = 4^o$.

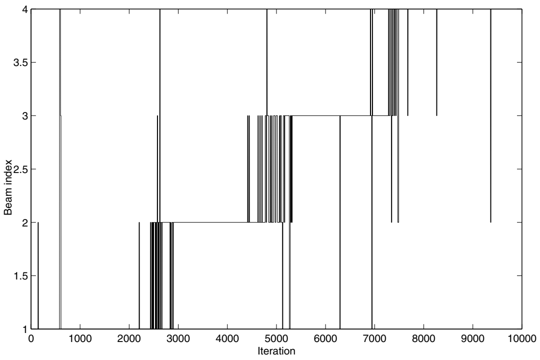

Fig. 6. Evolution of beam index for 60kmph in a noisy environment (SNR of 0dB).

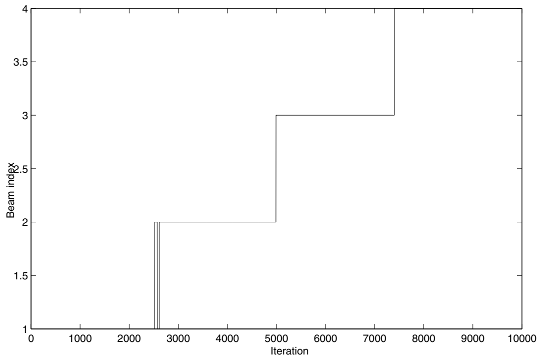

Fig. 7. Evolution of beam index for 60kmph in a "clean" environment (SNR of 30dB).

based on position would ideally occur, if the BS was to use the reverse link to estimate the angle of arrival. To serve as reference, we also add the performance of a genie receiver (called Genie in the figure), which has perfect knowledge of the channel, but chooses the beam according to the mobile angular position.

We can observe that the performance of our proposed method is very slightly superior to that of the method called "Angular Position". This is due to the fact that our approach changes dynamically the selected beam when the serving beam experiences a deep fade, even when the mobile does not change beam position-wise. Not surprisingly, we notice that, even for lower speeds, there is an error floor which is due to the interpolation errors across subcarriers.

V. Conclusion

In this paper, we investigated the use of the OFDM symbol structure to both estimate the channel and select the beam, in downlink switched-beam OFDM systems. To do so, we used a special downlink pilot symbol, designed by multiplexing beam-related pilot samples throughout the OFDM subcarriers. At the mobile, beam channels seen on each subcarrier are estimated, then the best serving beam is selected. For equalization purposes, an interpolation is used between estimated beam channels to fill the missing beam channel estimates in subcarriers allocated to the non-selected beams. Unlike previous works which based the beam selection on the uplink/downlink channel symmetry of the channel, and on uplink measurements, our approach uses downlink measurements obtained at the mobile. Results have shown that our new beam selection process is more resistant to noise when the mobile speed is small. Our proposed method has the advantage of using the same pilot symbols for channel estimation at the mobile, and beam selection.

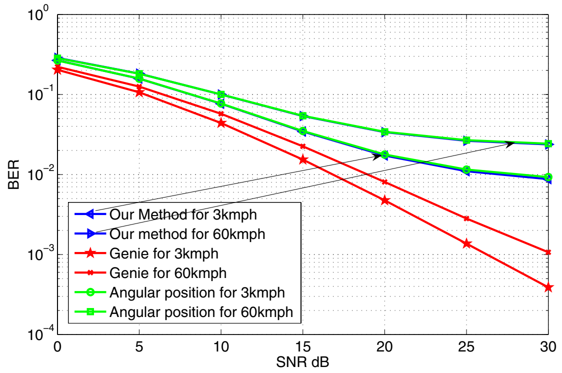

Fig. 8. SNR_dB vs BER for 4 antennas and different speeds.

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